CHAP ONE:

Passage of charged particles and radiation through matter.

1.0 Introduction:

→ Interaction of radiation with matter involves a transfer of energy from the radiation to matter with which it interacts. Matter consists of atomic nuclei and extra nuclear electrons. Radiation may interact with either or both of these constituents of matter. The probability of the occurence of any particular category of interaction depends on the type and energy of the radiation as well as on the nature of the absorbing medium.

→ Radiation can be classified into two general groups, charged and uncharged. Charged particles directly ionize the media through which they pass, while uncharged particles and photons can cause ionization only indirectly or by secondary radiation.

→ A moving charged particle has an electric field surrounding it, which interacts with the atomic structure of the medium through which it is passing. The interaction decelerates the particle and accelerates the electrons in the atoms of the medium. The accelerated electrons may acquire enough energy to escape from the parent atom. This process, whereby radiation "strips" off orbital electrons, is called ionization.

→ Uncharged moving particles have no electrical field, so they can only lose energy and cause ionization by such means as collisions or scattering. A photon can lose energy by photoelectric effect, compton effect, or pair production.

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Because ionizing radiation creates ions in pairs, the intensity of ionization of the specific ionization is defined as the number of ion-pairs formed per centimeter of travel in a given material. The amount of ionization produced by a charged particle per unit path length, which is a measure of its ionizing power, is roughly proportional to the particle's mass and the square of its charge as illustrated in the equation below.

$$I = \frac{mZ^2}{K.E} \qquad \text{——— (1)}$$

where : I is the ionizing power
m is the mass of the particle
Z is the number of unit charges it carries
K.E is its kinetic energy.

m for alpha particle is about 7300 times as large as m for a beta particle, and Z is twice as great, an alpha will produce much more ionization per unit path length than a beta particle of the same energy. This phenomenon occurs because the larger alpha particle moves slower for a given energy and thus acts on a given electron for a longer time.

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1.1 Interaction of charged Particle with matter:-

1.1.1 Interaction Mechanisms:-

Two principal features characterize the passage of charged particles in matter. These are loss of energy by the particle and deflection of the particle from its incident direction. These are the results of the following interactions.

1. Inelastic collisions with orbital electrons (excitation and ionization of atoms)
2. Radiative losses in the field of nuclei (Bremsstrahlung emission).
3. Elastic scattering with nuclei and
4. Elastic scattering with orbital electrons.

1.1.2 Interactions of Heavy Charged particles:-

Bethe Formula of stopping Power

The stopping power $\left(-\frac{dE}{dx}\right)$ of a material for a fast moving charged particle is given by the Bethe formula

$$S = -\left(\frac{dE}{dx}\right)_{coll} = \frac{4\pi e^4 Z^2}{m_0 v^2} NZB \qquad (2)$$

where $B = \left[\ln \frac{2m_0v^2}{I} - \ln\left(1-\frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$

where Ze is the charge of the incident particle, v its velocity, N the number density of atoms (number of atoms per unit volume) of the material having atomic number Z, m_0 the electron rest mass and e the electron charge. The quantity I is a material property called the mean excitation energy which is a logarithmic average of the excitation energies of the medium weighted by the

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The corresponding oscillator strengths. Except for elements with very low atomic number Z, the mean excitation energies in eV are approximately equal to $10Z$ [$I = (9.6 + 58.8^{-1.19})Z$]

At very low velocity ($v = \frac{c}{137}$ in case of hydrogen) the heavy ion neutralizes itself by capturing electrons for part of the time. This result in ~~arp~~ a rapid falloff of ionization at the very end of the range. On the other hand, at extremely high energies, with $v \simeq c$, ionization increases for several reasons. The relativistic contraction of coulomb field of the ion is one of them. Part of the energy is carried away as light.

a) Bragg's Rule:

It is generally assumed that chemical and atomic aggregation phenomena affects stopping power to a very limited extent. This is embodied in the Bragg rule for the evaluation of the mean excitation potential:

$$n \ln I = \sum n_i \ln I_i \qquad (3)$$

where I_i(eV) $= (9.6 + 58.8^{-1.19})Z$ for $Z > 12$

where n is the number density of electrons associated with element and I_i is the mean excitation potential for that element. The implication of this relation is that the stopping power in a compound is the sum of stopping powers of the individual elements. The increased validity of Bragg's ~~rule~~ law with increasing atomic charge relies on the increase dependence of I on inner-shell electrons, which are insensitive to chemical effects. Deviation from Bragg's rule should be more apparent at low energies for which logarithmic term in the Bethe formulae becomes a sensitive function of I.

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b) Scaling Law for stopping Power and Range:

To draw some conclusions of considerable practical importance, the Bethe stopping power formula can be written as

$$\frac{dE}{dx} = Z^2 \lambda(v) \qquad \text{——— (4)}$$

or, remembering that the kinetic energy of a particle of mass M is $E = M\mathcal{E}(v)$, where $\mathcal{E}$ is a function of the velocity only, we have, using E as a variable

$$-\frac{dE}{dx}(E) = Z^2 \lambda_E \frac{E}{M} \qquad \text{——— (5)}$$

or using v as a variable

$$-\frac{dE}{dx}(v) = \frac{Z^2}{M} \lambda_v \qquad \text{——— (6)}$$

The last two relations allow us to write the energy for any particle, once the energy loss as a function of energy is known for protons. In particular protons, deuterons and tritium of the same velocity have the same stopping power.

Similar scaling relations obtain for the range. Using the velocity as variable, one has

$$R_v(v) = \int_0^v \frac{dv}{(dv/dx)} = \frac{M}{Z^2} \int_0^v \frac{dv}{\lambda_v(v)} = \frac{M}{Z^2} \rho_v(v) \qquad (7)$$

or using energy as a variable

$$R_E(E/M) = \frac{M}{Z^2} \rho_E(E/M) \qquad \text{——— (8)}$$

The above mentioned equations for Range are not exact, for the neutralization phenomena occurring at the end of the range and other corrections are neglected; but it is sufficiently accurate for most cases.

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excluding very low energies. As an example of the application of the last equation mentioned above, we can verify that a deuteron of energy E has twice the range of a proton of energy E/2.

A semi empirical power law valid from a few Mev to 200 Mev for proton range - energy relation is $R(E) = (E/9.3)^{1.8}$ ——— (9)

where E is in Mev and R in meters of air.

→ The Thickness of material that just stops a particle of kinetic energy E, mass M and charge Z is called range R of the particle in that material.

→ $R(kg/m^2) = [R(m)][\rho(kg/m^3)]$ — 10

ρ is density of the particle in which the particle travels. The range measured in kg/m^2 is independent of state of matter. e.g A particle will have the same range whether it moves in ice, water or steam. Of course the measured range in metres will differ.

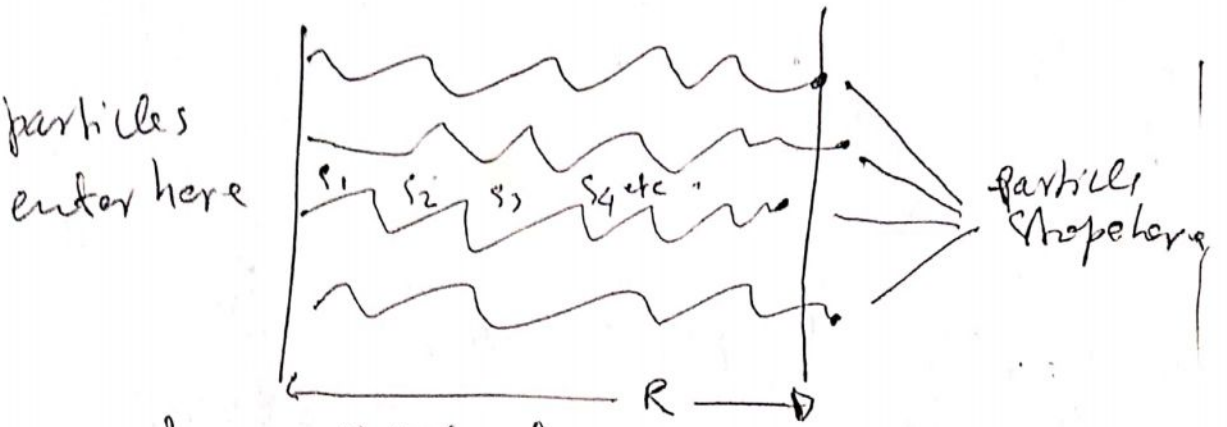

fig 1 Path length (S) and Range (R)

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There are semiempirical formulas that give the range as function of particle kinetic energy. For Alpha particles, the range in air at normal temperature and pressure is given by (11)

$$R(mm) = \exp\left[1.61\sqrt{T(MeV)}\right] \quad 1 \leq T \leq 4 MeV$$

$$R(mm) = (0.05T + 2.85)T^{3/2}(MeV) \quad 4 \leq T \leq 15 MeV$$

where T = kinetic energy of the particle in MeV.

If the range is known for one material, it can be determined for any other by applying the Bragg-Kleeman rule:

$$\frac{R_1}{R_2} = \frac{\rho_2}{\rho_1}\sqrt{\frac{A_1}{A_2}} \qquad (12)$$

where ρ_i and A_i are the density and atomic weight, respectively, of material i. For a compound or mixture, an effective molecular weight is used, obtained from the equation

$$\sqrt{A_{ef}} = \left(\sum_{i=1}^{L} \frac{w_i}{\sqrt{A_i}}\right)^{-1} \qquad (13)$$

where L = number of elements in the compound or mixture

w_i = weight fraction of i^{th} element

A_i = atomic weight of i^{th} element

Z_i = atomic number of i^{th} element

For a compound with molecular weight M the weight fraction is given by

$$w_i = \frac{N_i A_i}{M} \qquad (14)$$

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where N_i is the number of atoms in the compound of i^{th} element

Example 1

What is the effective molecular weight of water? What is it for air?

For H_2O (0.11% H, 0.89% O):

$$\sqrt{A_{ef}} = \left(\frac{0.11}{\sqrt{1}} + \frac{0.89}{\sqrt{16}}\right)^{-1} = 3 \quad A_{ef} = 9.$$

For air (22.9% O, 74.5% N, 2.6% Ar)

$$\sqrt{A_{ef}} = \left(\frac{0.229}{\sqrt{16}} + \frac{0.745}{\sqrt{14}} + \frac{0.026}{\sqrt{40}}\right)^{-1} = 3.84 \quad A_{ef} = 14.74.$$

Using the Bragg-Kleeman rule with air as one of the materials ($\rho = 1.23\ kg/m^3$, $\sqrt{A_{ef}} = 3.84$), one obtains

$$R(mm) = \left(3.2 \times 10^{-1}\right) \frac{\sqrt{A_{ef}}}{\rho(kg/m^3)} R_{air}(mm) \quad (15)$$

There are two ways to calculate range of Alphas in a material other than air and silicon.

1. The range in air should be obtained first using equation 11 and then the range in the material of interest should be calculated using eqn 15.
2. The range in silicon should be read off from the available figure and then the range in the material of interest should be calculated using eqn 12.

Example 2:

What is the range of 3 Mev alpha in gold?

$\rho_{Si} = 2.33 \times 10^3\ kg/m^3$

$\rho_{Au} = 19.32 \times 10^3\ kg/m^3$

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The range of alpha in silicon is 12.5 μm

using eqn 12.

$$\frac{R_{Si}}{R_{Au}} = \frac{\rho_{Au}}{\rho_{Si}}\sqrt{\frac{A_{Si}}{A_{Au}}} \Rightarrow R_{Au} = \frac{\rho_{Si}}{\rho_{Au}}\sqrt{\frac{A_{Au}}{A_{Si}}}\, R_{Si}$$

$$R_{Au} = \frac{2.33\times10^{3}}{19.32\times10^{3}} \times \sqrt{\frac{197}{28}} \times 12.6\times10^{-6} = 4\times10^{-6}\,m = 4\,\mu m$$

Using equations 18 and 15

$$R = 3.2\times10^{-1}\,\frac{\sqrt{197}}{19.32\times10^{3}}\,\exp\left(1.61\sqrt{T}\right) = 3.8\times10^{-3}\,mm = 38\,\mu m$$

Example 3:-

What is the range of a 10 Mev alpha particle in aluminium given that the range in silicon is $R_{Si} = 70\,\mu m$

solution:

$$R_{Al} = \frac{\rho_{Si}}{\rho_{Al}}\sqrt{\frac{A_{Al}}{A_{Si}}}\, R_{Si} = \frac{2.33\times10^{3}}{2.7\times10^{3}}\sqrt{\frac{27}{28}}\times 70\,\mu m$$

$$= 59\,\mu m$$

Using eqn 11 and 15

$$R_{Al} = (3.2\times10^{-1})\,\frac{\sqrt{27}}{2.7\times10^{3}}\left[0.05(10)+2.85\right]10^{3/2}\,mm$$

$$= 6.52\times10^{-5}\,m = 65\,\mu m$$

The ±6 of 6 μm is within the range of accuracy of the bragg-kleeman rule.

~~for other materials equation~~

The range of protons and deuterons in aluminium has been measured by Richel. His results are represented very well by the following two equations:-

$$\begin{cases} R(\mu m) = 14.21\,T^{1.5874} & 1\,Mev < T \le 2.7\,Mev \\ R(\mu m) = 10.5\,\dfrac{T^2}{0.68 + 0.434\,T} & 2.7\,Mev \le T \le 20\,Mev \end{cases} \quad (16)$$

For other materials equation (12) should be used after the range in aluminium is determined from eqn (16).

The range of protons and deuterons can be calculated from the range of alpha particle of same speed using the formula:

$$R(P,d) = 4\,\frac{M(P,d)}{M_\alpha}\,R_\alpha - 2(mm, air) \quad (17)$$

where R_α = range of α particle in air having the same speed as the deuteron or the proton,
M = mass of particle (1 for proton, 2 for deuteron),
M_α = mass of alpha particle = 4
for material other than air, the Bragg-Kleeman rule (eqn 15) should be used.
The fact that the alpha and proton or deuteron ranges are related by the same speed rather than the same kinetic energy is due to the dependence of $\frac{dE}{dx}$ on the speed of particle.

Example 4:

What is the range of 5 Mev deuteron in air?

solution:

Let us calculate the range of alpha particle with speed equal to that of 5 Mev deuteron. The K.E of alpha particle with the same speed

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will be found using the same corresponding eqn for the kinetic energy. Since $T = \frac{1}{2}MV^2$ for these non relativistic particles

$$T_\alpha = \frac{M_\alpha}{M_d} T_d = 2T_d = 10\,MeV$$

The range of 10 Mev alpha particle in air is

$$R = (0.05T + 2.85)T^{3/2} = 106 = 0.106\,m$$

The range of the 5 Mev deuteron in air is

$$R_d = 2R_\alpha - 2 = 210\,mm = 0.21\,m$$

Example 5:

What is the range of a 5 Mev deuteron in aluminium using the Brgg-kleeman rule (eqn 15) and the result of the previous example;

$$R_d(Al) = 3.2\times10^{-1}\,\frac{\sqrt{27}}{2.7\times10^3}\times210 = 0.129\,mm$$

$$= 129\,\mu m$$

1.1.3 Interaction of light charged particles:

Light charged particles are electrons and positrons. As all forms of ionizing radiation eventually results in a distribution of low-energy electrons, the interaction of light charged particles are of central importance in radiation biology. The large difference in mass between electrons and heavy charged particles has important consequences for interactions. Light charged particles deposit energy through two mechanisms: Collisional losses and Radiative losses.

a) Collisional losses =

- Electrons lose energy via interactions with orbital electrons in the medium.
- This leads to excitation of the atom or ionization

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- Energy loss via these mechanisms is called "collisional loss".
- Maximum energy transfer occurs in a "head on" collision between two particles of masses m and M and can be expressed as

$$T_{max} = \frac{mME}{(M+m)^2} \quad \text{— (18)}$$

where E is the kinetic energy of the incident particle.
- The electron collides with a particle of identical mass and thus large scattering angles are possible.
- The results is a track that is very tortuous instead of the straight path of a heavy charged particle.

b) Radiative Losses = bremsstrahlung:

- A second mechanism of energy loss is possible because of the small mass of the light charged particle.
- A charged particle undergoing a change in acceleration ~~the more energetic the bremsstrahlung~~ always emits "radiative" electromagnetic radiation called bremsstrahlung.
- The larger the change in acceleration, the more energetic the bremsstrahlung photon.
- For electrons, the bremsstrahlung photons have a continuous energy distribution that ranges downward from a maximum equal to the kinetic energy of the incoming electron.
- The efficiency of bremsstrahlung in elements of different atomic number Z varies nearly as Z^2.
- Notice that bremsstrahlung increases with electron kinetic energy and atomic number Z.

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i) Energy loss due to bremsstrahlung Emission:

For electrons or positrons with kinetic energy T(Mev) moving in a material with atomic number Z, the energy loss due to bremsstrahlung emission, $\left(\frac{dE}{dx}\right)_{rad}$ is given in terms of the ionization and excitation energy loss by:

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{ZT(Mev)}{750}\left(\frac{dE}{dx}\right)_{ion} \quad \text{——— (19)}$$

where $\left(\frac{dE}{dx}\right)_{ion}$ is the stopping power due to ionization - excitation.

Example 6

Consider an electron with T = 5 Mev. what fraction of its energy is lost ~~dice~~ as bremsstrahlung as it starts moving (a) in aluminium, and (b) in lead?

Solution:

a) If it travels in aluminium (Z = 13)

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{13(5)}{750}\left(\frac{dE}{dx}\right)_{ion} = 0.09\left(\frac{dE}{dx}\right)_{ion}$$

That is the rate of energy loss due to radiation is about 9% of $\left(\frac{dE}{dx}\right)_{ion}$.

(b) The same electron moving in lead

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{82(5)}{750}\left(\frac{dE}{dx}\right)_{ion} = 0.55\left(\frac{dE}{dx}\right)_{ion}$$

In this case the rate of radiation energy loss is 55% of $\left(dE/dx\right)_{ion}$.

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The Total energy radiated as bremsstrahlung is approximately equal in Mev to:

$$T_{rad} = 4.0 \times 10^{-4} Z T^2 \quad \text{——— (20)}$$

~~What~~ Example 7:

What is the total energy radiated by the electron in example 6?

Solution:

Using equation (20)

(a) in aluminium:

$$T_{rad} = 4.0 \times 10^{-4} Z T^2 = 4.0 \times 10^{-4} \times 13 \times 5^2$$
$$= \underline{0.130 \text{ Mev}}$$

(b) in lead:

$$T_{rad} = 4.0 \times 10^{-4} Z T^2 = 4.0 \times 10^{-4} \times 82 \times 5^2$$
$$= \underline{0.820 \text{ Mev}}$$

The total stopping power for electron or positron will be given by ~~the eq~~:

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{ion} + \left(\frac{dE}{dx}\right)_{rad} = \left(1 + \frac{ZT}{750}\right)\left(\frac{dE}{dx}\right)_{ion} \quad \text{——— (21)}$$

If the particle moves in a compound or mixture instead of pure elements, an effective atomic number Z_{ef} should be used in equation 20 and 21. The value of Z_{ef} is given by:

$$Z_{ef} = \frac{\sum_{i=1}^{L} (w_i/A_i) Z_i^2}{\sum_{i=1}^{L} (w_i/A_i) Z_i} \quad \text{——— (22)}$$

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where C = number of element in compound or mixture
w_i = weight of fraction of i^{th} element
A_i = atomic weight of i^{th} element
Z_i = atomic number of i^{th} element

for a compound with molecular weight M, the weight fraction is given by

$$w_i = \frac{N_i A_i}{M} \quad \text{---(23)}$$

where N_i is the number of atoms in the compound of i^{th} element.

ii) Range of electron and positrons:

The semiempirical equation giving the range of electrons for the energy range 0.3 Kev to 30 Mev has been developed by Tabata, Ito, and Okabe, based on the experimental results available until 1972. This equation, indicated from now on as the TIO equation, has the following form

$$R\,(kg/m^2) = a_1 \left\{ \frac{\ln\left[1 + a_2(\gamma-1)\right]}{a_2} - \frac{a_3(\gamma-1)}{\left[1 + a_4(\gamma-1)\right]^{a_5}} \right\} \quad \text{---(24)}$$

where

$$a_1 = \frac{2.335\,A}{Z^{1.209}} \qquad a_3 = 0.9891 - (3.01\times10^{-4}Z)$$

$$a_2 = 1.78\times10^{-4}Z \qquad a_4 = 1.468 - (1.180\times10^{-2}Z)$$

$$a_5 = \frac{1.232}{Z^{0.109}} \quad \text{---(25)}$$

$$\gamma = \frac{T + mc^2}{mc^2} = \frac{T + 0.511}{0.511}$$

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In the case of absorbers that are mixtures or compounds, the atomic number Z and atomic weight A to be used in eqn (25) are given by

$$Z_f = \sum_i^L w_i Z_i \qquad (26)$$

$$A_f = Z_f \left(\sum_{i=1}^{L} w_i \frac{Z_i}{A_i} \right)^{-1} \qquad (27)$$

where A_i, w_i and Z_i have their usual meaning.

Example 8:

What is the range of 1 Mev electron in gold? ($Z = 79$, $A = 197$)

Solution:

$$a_1 = \frac{2.335\,(197)}{79^{1.209}} = 2.336$$

$$a_2 = (1.78 \times 10^{-4})(79) = 0.01406$$

$$a_3 = 0.9891 - (3.01 \times 10^{-4} \times 197) =$$

$$a_4 = 1.468 - (1.18 \times 10^{-2})(79) = 0.5358$$

$$a_5 = \frac{1.232}{79^{0.109}} = 0.765$$

$$\gamma = \frac{1.511}{0.511} = 2.957$$

$$R = 2.336 \left[\frac{\ln(1 + 0.0275)}{0.01406} - \frac{1.8885}{1.895} \right] = 2.18 \text{ kg/m}^2$$

$$= 0.218 \text{ g/cm}^2$$

Since the density of gold is 19.3×10^3 kg/m^3, the range in μm is

$$R = \frac{2.18}{19.3 \times 10^3} = 1.13 \times 10^{-4} \text{ m} = 113 \text{ μm}$$

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Example 9

What is the range of 1 Mev electrons in aluminium? (Z = 13, A = 27).

Solution:

$$a_1 = \frac{2.335(27)}{13^{1.209}} = 2.837$$

$$a_2 = (1.78\times10^{-7})(13) = 2.314\times10^{-3}$$

$$a_3 = 0.9891 - (3.01\times10^{-4})(13) = 0.985$$

$$a_4 = 1.468 - (1.18\times10^{-2})(13) = 1.3146$$

$$a_5 = \frac{1.232}{13^{0.109}} = 0.9315$$

$$R(kg/m^2) = 2.837\left(\frac{\ln 1.0043}{0.00231} - \frac{1.928}{3.457}\right)$$

$$= 3.93\ kg/m^2 = 0.393\ g/cm^2$$

density of Al $= 2.7\times10^3\ kg/m^3 \Rightarrow R = \frac{3.93}{2.7\times10^3} = 1460\ \mu m$

(c) Transmission of Beta particle:

Beta particles have a continuous spectrum extending from zero energy up to maximum kinetic energy E_{max}. The number of betas $N(t)$ transmitted through a thickness t is given by

$$N(t) = N(0)\,e^{-\mu t} \qquad (28)$$

where μ is the mass absorption coefficient. The value of μ has been determined experimentally as function of the maximum beta energy and is given by:

$$\mu\,(m^2/kg) = 1.7\,E_{max}^{-1.14} \qquad (29)$$

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1.2 Interaction of Gamma and X-rays with matter.

1.2.1 Interaction Mechanisms:-

There are 12 possible processes by which photons (X-rays and γ-rays) may interact with matter. These are classified in Table 1

Table 1 = Photon Interaction with matter

	Type of Interaction ⇒ / Interaction with ↓	Complete absorption of photons	Elastic scattering (coherent)	Inelastic scattering (Incoherent)
I.	Atomic electrons	photo electric effect $\sigma_{pe} \propto Z^4$ (low energy) $\propto Z^5$ (high energy	Rayleigh Scattering $\sigma_R \propto Z^2$ (low energy limit)	Compton scattering $\sigma \propto Z$
II	Nucleons	photo nuclear reaction ($h\nu \geq 10$ MeV) $(\gamma, n), (\gamma, p), (\gamma, f)$ etc $\propto Z$.	Elastic nuclear scattering	Nuclear resonance scattering
III	Electric field of charged particle	Pair production a) Field of Nucleus $K_n \propto Z^2 (h\nu) \geq 1.02$ MeV b) Field of electron $K_e \propto Z (h\nu) \geq 2.04$ MeV	Delbruck Scattering	
IV	Mesons	photomeson production $h\nu \geq 140$ MeV		

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Among these large number of possible interaction mechanisms, only four major types play important role in radiation measurement: photoelectric absorption, compton scattering, pair production and Rayleigh scattering. All these processes lead to partial or complete transfer of photon energy to electron.

a) Photoelectric ~~effect~~ Absorption:

In the photoelectric absorption process, a photon undergoes an interaction with an absorber atom in which the photon completely disappears. In it, place an energetic photoelectron is ejected by the atom from one of its bound shells. The interaction is with the atom as a whole and can not take place with free electrons. For γ-rays of sufficient energy, the most probable origin of the photoelectron is the most tightly bound or K-shell of the atom. The photoelectron appears with energy given by

$$E_{e^-} = h\nu - E_b \quad \text{——(30)}$$

where $h\nu$ is the energy of the incident photon and E_b is the binding energy of the photoelectron in its original shell.

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The photoelectric cross section strongly depends upon the atomic number of the absorber and the energy of the photon. It is approximately given by

$$\sigma_{PE} = \frac{Z^n}{E_\gamma^{3.5}} \qquad \text{——— (31).}$$

where the exponent n varies between 4 and 5 over the gamma-ray energy region of interest.

b) Compton Scattering:

As the energy of photon increase above the k-edge, cross section for the photo electric absorption of photon becomes rapidly insignificant. The important energy loss mechanism beyond this point and upon around 1.5 Mev photons, is Compton scattering.

Compton scattering occurs when a photon of medium energy undergoes an elastic collision with a free or nearly free electron. In matter, of course, the electrons are bound, however, if the photon energy is high with respect to the binding energy, the binding energy can be ignored and the electrons can be essentially free.

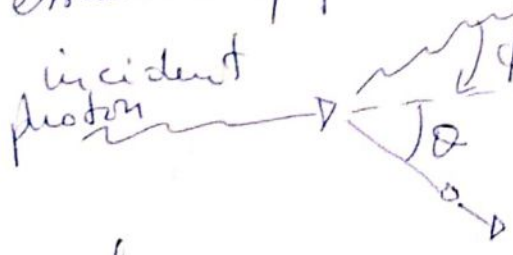

fig 2 = Kinematics of compton scattering.

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The incoming gamma-ray photon is deflected through an angle θ with respect to the original direction. The photon transfers a portion of its energy to the electron (assumed to be initially at rest), which is then known as recoil electron. Because all angles of scattering are possible, the energy transferred to the electron can vary from zero to a large fraction of the gamma-ray energy

By conservation of energy

$$h\nu = h\nu' + T = h\nu' + m_0c^2\left[\frac{1}{\sqrt{1-v^2/c^2}} - 1\right] \quad (32)$$

By conservation of momentum

$$\frac{h\nu}{c} = \frac{h\nu'}{c}\cos\phi + \frac{m_0 v}{\sqrt{1-v^2/c^2}}\cos\theta \quad \text{x-component} \quad (33)$$

$$0 = \frac{h\nu'}{c}\sin\phi - \frac{m_0 v}{\sqrt{1-v^2/c^2}}\sin\theta \quad \text{y-component} \quad (34)$$

from simultaneous equations for conservation of energy and momentum the expression that relates the energy and the scattering angle for any given interaction can be shown to be:-

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1-\cos\theta)} \quad (35)$$

where m_0c^2 is the rest mass energy of the electron (0.511 Mev).

The probability that the photon will be compton scattered falls off steadily with increasing energy of photons. Its dependence on the atomic number of photons.

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Its dependence on the atomic number of absorber has been found to be very little.

$$\sigma_{cs} = \frac{Z}{E_\gamma} \qquad \text{——— (36)}.$$

Example 9:

What fraction of their energies do 1 Mev and 0.1 Mev photons lose if they are scattered through an angle of 90°?

solution:

(i) for 1 Mev photon

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1-\cos\theta)} = \frac{1\,\text{Mev}}{1 + \frac{1\,\text{Mev}}{0.511\,\text{Mev}}(1-\cos 90^\circ)} = 0.338\,\text{Mev}$$

The fraction energy loss is thus.

$$1 - \frac{h\nu'}{h\nu} = \frac{1 - 0.338}{1} = 0.612 = 61.2\%$$

(ii) in the case of 0.1 Mev gamma rays the energy of the scattered photon is 0.0835 Mev and the fractional energy loss is only 16.5%.

Notice that the photon of greater energy loses greater fraction of its energy in the energy range considered.

Example 10: Maximum energy of compton recoil.

Compute the maximum energy of the compton Recoil electrons resulting from the absorption in Al of 2.19 Mev γ-rays.

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solution:

The recoil electron maximum energy (E_{max}) corresponds to the minimum energy of scattered photon $h\nu'_{min}$.

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1-\cos\theta)}$$

$$\Rightarrow h\nu'_{min} = \frac{h\nu}{1 + \frac{2h\nu}{m_0c^2}} \quad \cos\theta = -1 \text{ at minimum value.}$$

$$\Rightarrow E_{max} = h\nu - h\nu' = h\nu\left(1 - \frac{1}{1 + 2\frac{h\nu}{m_0c^2}}\right) = \frac{h\nu}{1 + \frac{m_0c^2}{2h\nu}}$$

Substituting $h\nu = 2.19$ Mev we obtain

$$E_{max} = \underline{\underline{1.961 \text{ MeV}}}.$$

c) pair production:

If the gamma ray energy exceeds twice the rest mass energy of an electron (1.02 Mev), the process of pair production is energitically possible. In pair production process the photon disappears and its materialization into electron - positron pair takes place. The energy of the photon partly appears as the rest masses of the two particles and partly as the kinetic energies of the electron (E_e) and positron (E_p).

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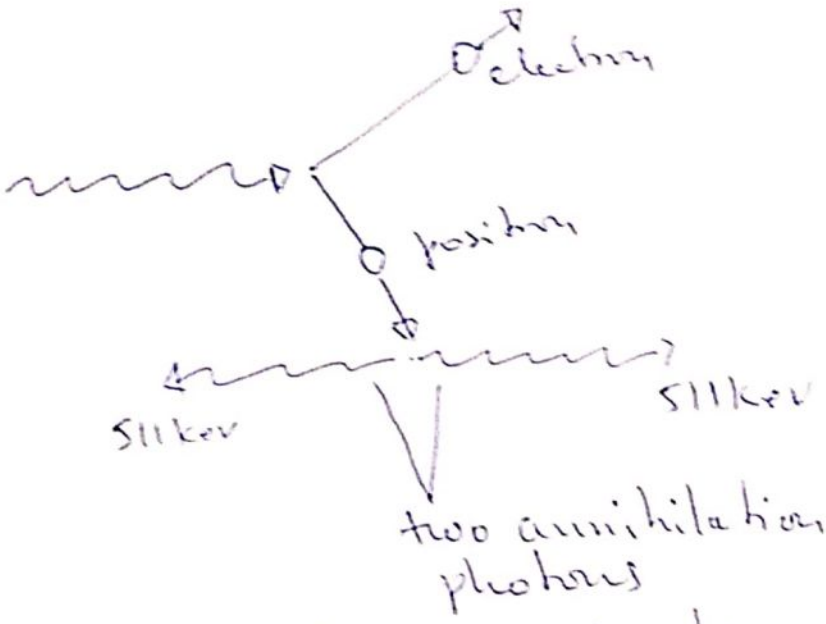

fig 3 Pair production and Pair Annihilation.

$$h\nu = E_e + E_p + 2m_0c^2 \quad \text{——} (37).$$

Note:

→ The available energy $(h\nu - 2m_0c^2)$ can be divided into any proportion between electron and positron but in general it is almost divided equally.

→ Pair production can take place in the presence of a nucleus so as to conserve momentum by recoil of nucleus.

→ After production of a pair, the positron and electron are projected in a forward direction and lose their kinetic energy by excitation, ionization and bremsstrahlung, as with any other high-energy electron. When the positron has expended all its kinetic energy, it combines with an electron to produce two quanta of 0.511 Mev each of annihilation photons.

→ The cross section of the pair production ~~process~~ ~~both~~ increases both as energy of photon and atomic number Z of the absorber.

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$\sigma_{pp} \propto Z^2 \ln E$ ——— (38).

This means that pair production is most important process with photons of high energy in heavy elements.

d) Rayleigh Scattering:

If the photon energy is smaller than the binding energy of the electron, then the electron is not removed by photon from its shell. It only vibrates after absorbing the photon. The vibrating photon acts as a dipole and thus emit photons of same energy in the forward direction. Because the outgoing photon energy remain unaltered and electron of the medium is neither removed nor excited, the process is also called coherent scattering. Rayleigh scattering generally occurs at higher Z materials.

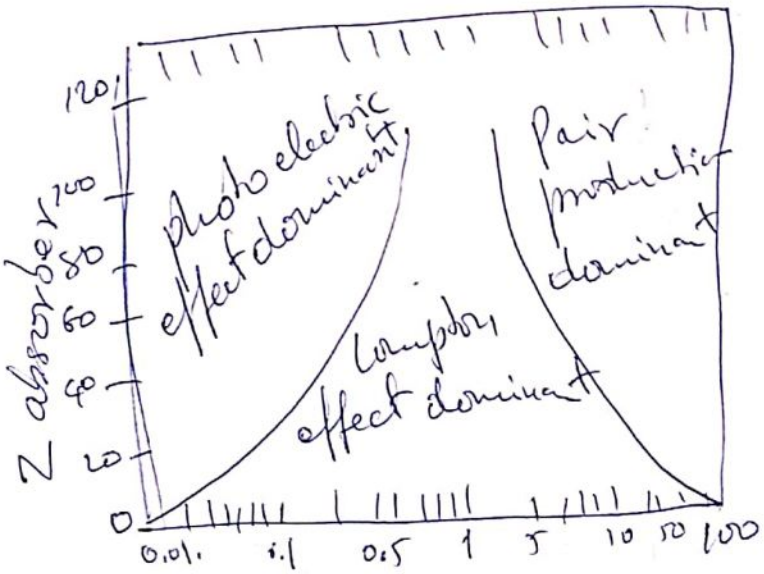

fig 4 The relative importance of the three major types of photon interaction. The lines show the values of Z and hν for which the two neighboring effects are just equal.

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e) Photonuclear reactions:

When the photon energy approaches the binding energy of the nucleon in the nucleus it is possible for a photon to initiate a nuclear reaction such as (γ, n), (γ, p), (γ, d), (γ, f) etc. The cross section of such reactions is generally very low compared to total cross section for interaction with atomic electrons. Hence energy lost by these photonuclear reactions is not that important upto photon energy of nearly 10 Mev.

1.1.4 Gamma Ray Attenuation:

consider a beam of photons of intensity I_0 incident upon a plane of absorbing material as shown

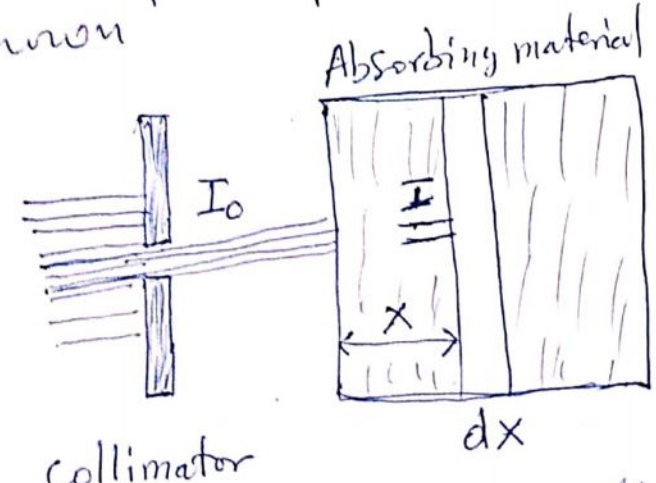

fig 5: Gamma ray attenuation.

At a depth x within the material this intensity is reduced to I due to interaction along its way within an incremental thickness dx. There is a further reduction in I by dI.

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The probability for interaction within dx is $\frac{dI}{I}$. Thus the probability for interaction per unit thickness is:

$$\mu = \frac{dI}{I}\left(\frac{1}{dx}\right) \quad \text{——— (39)}$$

In terms of μ we may write the decrease in intensity within dx

$$-dI = \mu I dx \quad \text{——— (40)}$$

This simple differential equation, when solved by using the boundary condition that $I = I_0$ at $x = 0$, yields:

$$I = I_0 e^{-\mu x} \quad \text{for good geometry} \quad \text{——— (41)}$$

$$I = B \times I_0 e^{-\mu x} \quad \text{for broad beam geometry} \quad \text{——— (42)}$$

where B is build up factor, which accounts for scattered radiation reaching the reference point. B is a function of shield material and its thickness and energy of the radiation and also a particular quantity being observed.

The linear attenuation coefficient μ is related to the total microscopic cross section σ_t by

$$\mu = N\sigma_t \quad \text{——— (43)}$$

Where N is the number of targets per unit volume. For this reason μ is sometimes referred to as macroscopic cross section. If we neglect minor interactions, the linear attenuation coefficient is the sum of the individual attenuation coefficients for the individual interactions

$$\mu = \mu_{PE} + \mu_{es} + \mu_{pp} \quad \text{——— (44)}$$

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Half Value Thickness (HVT):

It is the thickness that describes the average travelled of an absorber at which the intensity of the incident beam falls to its half value.

$$\mu = \frac{0.693}{HVT} \quad \text{——— (45)}$$

Mean free-path:

It is the quantity that describes the average distance travelled by a photon before absorption. The mean free path is given by

$$X_m = \frac{1}{\mu} \quad \text{——— (46)}$$

Mass Attenuation Coefficient (μ_m):

Mass attenuation coefficient is the probability of interaction per unit of path length expressed in terms of mass/area. It is obtained by dividing the linear attenuation coefficient by the density (ρ) of the material.

$$\mu_m = \frac{\mu}{\rho} = \frac{1}{\rho}(\mu_{PE} + \mu_{CS} + \mu_{PP}) \quad \text{——— (47)}$$

At a given γ-ray energy, the mass attenuation coefficient is independent of the physical state of a given absorber. For example it is the same for water whether present in vapour or liquid form.

The mass attenuation coefficient of a compound or mixture of elements can be calculated from

$$\left(\frac{\mu}{\rho}\right)_{compound} = \sum_i w_i \left(\frac{\mu}{\rho}\right)_i \quad \text{——— (48)}$$

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where the W_i factors represent the weight fraction of element i in the compound or mixture. In terms of the mass attenuation coefficient, the attenuation law for gamma rays now takes the form

$$I = I_0 e^{(-\mu_m \rho x)} \quad \text{——— (49)}$$

A unit very often used for expressing thickness is the surface density or mass thickness. This is given by the mass density of the material times its thickness in normal units of length, ie mass thickness = mass x density x thickness

$$t = \rho x \quad \text{——— (50)}$$

Mass thickness units are more convenient than normal units because they are more closely related to the density of interaction centers. They thus have the effect of normalizing materials of different mass densities.

Note =

→ Equal mass thickness of different materials will have roughly the same effect on the same radiation.

In terms of mass thickness and mass attenuation ~~Coefficients~~, ~~becomes~~ the attenuation law thus becomes:

$$I = I_0 e^{(-\mu_m)\rho x} = I_0 e^{(-\mu_m)t} \quad \text{——— (51)}$$

Example 11 =

The radioisotope ^{24}Na emits γ-rays of energies 1.378 MeV and 2.754 MeV in succession.

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After passing through, 27.5 gm/cm^2 of lead (density = 11 gm/cm^3). Calculate their relative intensities. The linear absorption coefficients are 48 and 62 respectively for the compounds

Solution:

$\gamma_1 = 1.378$ Mev $\quad \mu_1 = 48\ m^{-1} \quad \rho_b = 11\ gm/cm^3$

$\gamma_2 = 2.754$ Mev $\quad \mu_2 = 62\ m^{-1} \quad t = 27.5\ gm/cm^2$

I_0 is the same before attenuation.

Therefore:

$$I_1 = I_0 e^{-\mu_1 x} = I_0 e^{-\mu_m t} = I_0 \exp\left[\frac{-0.48 \times 27.5}{11}\right]$$

$$I_2 = I_0 e^{-\mu_2 x} = I_0 e^{-\mu_m t} = I_0 \exp\left[\frac{-0.68 \times 27.5}{11}\right]$$

$$\Rightarrow \frac{I_1}{I_2} = \underline{\underline{1.42}}$$

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Interaction of Neutrons:

Neutrons are uncharged, no coulombic force into play and thus a neutron possesses free access to nucleus of all atoms.

For neutron to interact with matter ie for the nuclear force to act, they must either enter the nucleus or come sufficiently close to it. The type of the interaction taking place between a neutron and a nucleus differs depending upon the kinetic energy of the incident neutron.

Energy classification:

For the purpose of study of neutron interactions, neutrons are classified as below.

- Thermal neutrons energy below 0.5 eV
- intermediate neutrons 0.5 ev – 100ker
- Fast neutrons 100 kev – 20 Mev
- High energy neutrons above 20 Mev

Study of the neutron interaction with matter requires the knowledge of neutron energy spectrum. for many application the spectrum is poorly known. All neutrons are fast by birth and lose energy by colliding elastically with atoms in their enviroment and then after being slowed down to thermal energies they are captured by the nuclei of the absorbing medium.

Neutron sources:

The most prolific source of neutrons is the nuclear reactor.

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- The splitting of a uranium or a plutonium nucleus in a nuclear reactor is accompied by the emission of ~~several~~ several neutrons. These fission neutrons have a wide range of energies, peak at $\simeq 0.7$ Mev and have a mean value of $\simeq 2$ Mev.

- Copious neutron beams may be produced in accelerators by many different reactions for example bombardement of beryllium by high-energy deuterons in a cyclotron produces neutrons according to the reaction =

$$ {}^{9}_{4}Be + {}^{2}_{1}D \longrightarrow \left({}^{11}_{5}Be\right)^{*} \longrightarrow {}^{10}_{5}B + {}^{1}_{0}n $$

Another commonly used neutron source depends on the bombardment of beryllium with alpha particles. The reaction, in this case, is

$$ {}^{9}_{4}Be + {}^{4}_{2}He \longrightarrow \left({}^{13}_{6}C\right)^{*} \longrightarrow {}^{12}_{6}C + {}^{1}_{0}n $$

Radium, polonium, and plutonium are used as the source of alpha particles. Photoneutrons are the other important source of neutrons. In this process gamma radiations from ^{24}Na, ^{226}Ra, ^{124}Sb, ^{72}Ga and ^{140}La bombarding ^{9}Be

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And $^{2}_{1}H$ give neutrons (having an energy distribution).

Interaction Mechanisms

There are number of processes by which a neutron can interact with matter.

(i) Elastic Scattering (n, n) : In elastic collision both the momentum and kinetic energy of ~~scattering~~ the system of neutron and interacting nucleus are conserved. In each collision with a stationary nucleus, the neutron transfers part of its kinetic energy to the nucleus, depending on the angle through which the neutron is scattered.

(ii) Inelastic scattering : In the range of energy above 0.5 Mev inelastic scattering begins to occur [(n, n), (n, 2n), (n, γ) type of reactions]. In this case a part of kinetic energy of the incident neutron is given off in the form of one or more gammas. This process allways takes place through the formation of compound nucleus. This type of interaction is not possible unless the neutron energy exceeds a certain threshold.

(iii) Non elastic scattering (Nuclear reaction involving emission of charged particles) : Non elastic ~~scattering~~ reactions occur at high energies [(n, α), (n, P) type].

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These are the reactions with energy thresholds in which the neutron causes the emission of charged particles (protons or other heavier particles) from the target nucleus. An example of particular importance in biological tissue is the (n, p) reaction of ^{14}N with slow neutrons: $^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}H$. This reaction produces a proton of 0.58 Mev energy.

(iv) radiative capture (n, γ) = Nuclear process in which a neutron is captured by the target nucleus and the excess energy emitted as radiation, is called radiative capture process. Conditions for such reactions are especially favorable during slow neutron (with energy < 1ev) interaction with medium -
This process is extensively used for the production of isotopes by exposing stable nuclides to slow neutrons in a nuclear reactor.

(V) Spallation reaction = In this process the target nucleus is fragmented with the emission of several particles, often including neutrons. The process becomes significant only at neutron energies of about 100 Mev or greater.

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(vi) Nuclear fission (n, f) : in certain reactions involving heavy atomic nuclei, the capture of neutron results in the formation of an excited state of a compound nucleus so unstable that it splits up into two smaller nuclei. This process is of fundamental importance for the operation of nuclear reactors.

Attenuation of neutrons

$$I = I_0 e^{-\sigma N t} = I_0 e^{-\Sigma t}$$

where $\Sigma = \sigma N$ = microscopic cross section for the absorbing material.

I_0 = initial intensity of incident neutrons,

I = transmitted intensity of neutrons after passing through t cm and t thickness of the target.

N = number of absorber atoms per cm^3

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The macroscopic cross section:

$$\Sigma_i\,(m^{-1}) = N(\text{atoms}/m^3)\left[\sigma_i\,(m^2)\right]$$

Σ_i = probability that an interaction of type i will take place per unit distance of travel of a neutron moving in a medium that has N atoms/m^3.

If a parallel beam of monoenergetic material of intensity $I(0)$ impinges upon a material of thickness t the number of neutrons that emerge without having interacted in the material is

$$I(t) = I(0)\, e^{-\Sigma_t t}.$$

where $\Sigma_t = \Sigma_s + \Sigma_i + \Sigma_a + \cdots =$ total macroscopic cross section.

As with γ rays $e^{-\Sigma_t t}$ = probability that a neutron travel with no interaction.

The average distance b/w two successive interaction is

$$\lambda = \frac{\int_0^\infty x\, e^{-\Sigma x}\, dx}{\int_0^\infty e^{-\Sigma x}\, dx} = \frac{1}{\Sigma}$$

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Interaction of neutrons with matter (Reaction rate).

The number of reaction per second, R, taking place in this target may be written as :

$$R\ (\text{reaction/s}) = \begin{pmatrix}\text{neutron per } m^2 s \\ \text{hitting the target}\end{pmatrix}\begin{pmatrix}\text{target exposed} \\ \text{to the beam}\end{pmatrix} \times \begin{pmatrix}\text{probability of interaction} \\ \text{per n/m}^2 \text{ per nucleus}\end{pmatrix}$$

$$= I\ (n/m^2 s)\,[N\ (\text{nuclei}/m^3)]\,[\bar{a}\ (m^2)]\,[t\ (m)] \times [\bar{\sigma}\ (m^2)] \quad —$$

$\bar{\sigma}\ (m^2)$ = probability that interaction will occur per target nucleus per n per m^2 hitting the target.

$$\bar{\sigma}_{total} = \bar{\sigma}_s + \bar{\sigma}_i + \bar{\sigma}_f + \cdots$$

$$\bar{\sigma}_a = \bar{\sigma}_\gamma + \bar{\sigma}_f$$

$\bar{\sigma}_s$ = elastic scattering cross section
$\bar{\sigma}_i$ = inelastic " " "
$\bar{\sigma}_\gamma$ = Compton " " "
$\bar{\sigma}_f$ = fission " " "

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Example:

What are the macroscopic cross sections Σ_s, Σ_a and Σ_t for thermal neutrons in graphite? The scattering cross section is $\sigma_s = 4.8$ b and absorption cross section is $\sigma_a = 0.00345$. What is the mean free path?

For graphite $\rho = 1.6 \times 10^3$ kg/m^3 and $A = 12$

Therefore,

$$N = \frac{\rho N_A}{A} = \frac{(1.6 \times 10^3)\ 0.6023 \times 10^{24}}{12 \times 10^{-3}}$$

$$= 0.0803 \times 10^{30} \text{ atoms/m}^3$$

$$\Sigma_s = N\sigma_s = 0.0803 \times 10^{30} \times (4.8 \times 10^{-28}) = 38.5 \text{ m}^{-1}$$

$$= 0.385 \text{ cm}^{-1}$$

$$\Sigma_a = N\sigma_a = (0.0803 \times 10^{30})(0.0034 \times 10^{-28}) = 0.027 \text{ m}^{-1}$$

$$= 0.00027 \text{ cm}^{-1}$$

$$\Sigma_t = \Sigma_s + \Sigma_a = 38.53 \text{ m}^{-1} = 0.3853 \text{ cm}^{-1}$$

The mean free path is $\lambda = \frac{1}{\Sigma_t} = 0.0259 \text{ m} = \underline{2.59 \text{ cm}}$

For a mixture of several isotopes the macroscopic cross section Σ_i is calculated

by $\Sigma_i = \sum_j N_j \cdot \sigma_{ij}$

where σ_{ij} = microscopic cross section of isotope j for the the reaction i, $N_j = w_j \rho N_A / A_j$

w_j = weight fraction of j^{th} isotope in the mixture

ρ = density of mixture.

The above equation for Σ_i assumes that all isotopes act independently, ie the chemical crystal binding force are negligeable. In certain case the binding forces may not be neglected.

Example:

What is the total macroscopic absorption cross section of natural uranium?

natural uranium consist of 0.711 percent of ^{235}U and the rest is ^{238}U.

for thermal n, the absorption cross section are $\sigma_a(^{235}U) = 678$ b and $\sigma_a(^{238}U) = 2.73$ b

density of U $= 19.1 \times 10^3$ kg/m^3

$$\Sigma_a = 0.00711 (19.1\times10^3) \cdot \frac{0.6023\times10^{24}}{235\times10^{-3}} (678\times10^{-28})$$

$$+ 0.99289 (19.1\times10^3) \frac{0.6023\times10^{24}}{238\times10^{-3}} (2.73\times10^{-28})$$

$$\Sigma_a^{(U)} = (23.6 + 13.1)\,m^{-1} = 36.7\,m^{-1} = 0.367\,cm^{-2}$$

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The $_0^1n$ flux:

$R = nv\Sigma$ (react^{o}/m^3.s)

$\phi = nv$ (n/m^2.s) = $_0^1n$ flux

Using the expression for the reaction rate becomes,

$R_i = \phi\Sigma_i$ [(react^{o} of type i)/m^3.s]

Example 3.

What is the fission rate at certain point inside a nuclear reactor where the neutron flux is known to be $\phi = 2.5\times10^{14}$ neutrons/m^2.s, If a thin foil of ^{235}U is placed there? The fission cross section for ^{235}U is $\sigma_f = 577$

Soln:

$$\Sigma_f = N\sigma_f = (19.1\times10^3)\frac{0.6024\times10^{24}}{235\times10^{-3}}\times(577\times10^{-28})$$

$= 2824\ m^{-1} = 28.24\ cm^{-1}$

and $R_f = \phi\Sigma_f = (2.5\times10^{14})282$

$= 7.06\times10^{17}$ fission/cm^3.s

$= 2.06\times10^{11}$ fissions/cm^3.s

Another quantity related to the flux and used in radiation exposure calculations is the $_0^1n$ fluence F, defined by $F(n/m^2) = \phi t$

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Detection of high energy radiation:

2.1 Introduction

Generally we are interested in knowing one or more of the following

(i) simple detection
(ii) Quantity of radiation
(iii) Energy of the radiation
(iv) nature of the radiation

2.2 properties of radiation detectors:

(i) Intrensic efficiency or sensitivity

intrensic efficiency E_i, of a detector is the measure of its ability to detect radiation and generally defined as the ratio of the number of rays of a given radiation (α, β or γ) detected to the number of rays incident on the sensitive volume of the detector.

$$E_i = \frac{\text{Number of rays detected by the detector}}{\text{Number of rays incident on the sensitive volume of the detector.}}$$

The higher the intrensic efficiency of a detector the better it is for use in radiation detection. This efficiency depends upon the linear attenuation coefficient (μ linear) and the thickness of the sensitive volume

(ii) Dead time or resolving time (τ):

Dead time or resolving time is a measure of the ability of a detector to function accurately at high count rate or radiation flux (intensity). For any detector, there is a small but finite interval τ, between the time when the ray interacts with a detector and the time when the detector responds and the event is

recorded. This interval τ is known as "dead time" or resolving time of the detector.

(iii) Energy resolution:

Ability of a detector to distinguish b/w two radiations of different energies (e.g two x-rays of different energies) as its energy resolution. Full width at half maximum (FWHM) which is commonly used as a measure of energy resolution, represents the minimum difference necessary b/w the energies of two γ-rays, if they are to be identified as having different energies.

If the FWHM of a detector is 20keV then two γ-rays with difference in energy less than 20keV cannot be distinguished by this detector. A lower value of FWHM/indicates a better energy discrimination capability or energy resolution.

2.3 Gas filled detectors:

The first action of high-energy radiation on matter is the production of ionization. The measurement of amount of ionization produced is the basis of gas-filled detectors. In general, it is not possible to measure the amount of ionization produced in matter except in gas and some solids known as semiconductors.

2.3.1 Mechanism

In figure 2.1, there is no voltage difference ($V = 0$) between the two electrodes. The ion pairs produce in the gas to form neutral atoms or molecules, and no current follows in the circuit.

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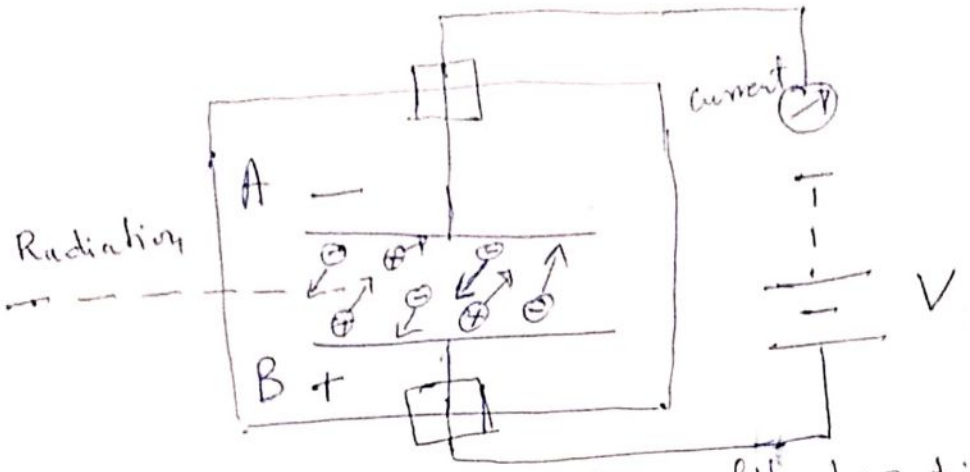

fig 2.1: Schematic of gas-filled radiation detector. A and B are two electrodes which collect the ion pairs produced in the gas by the passage of a radiation.

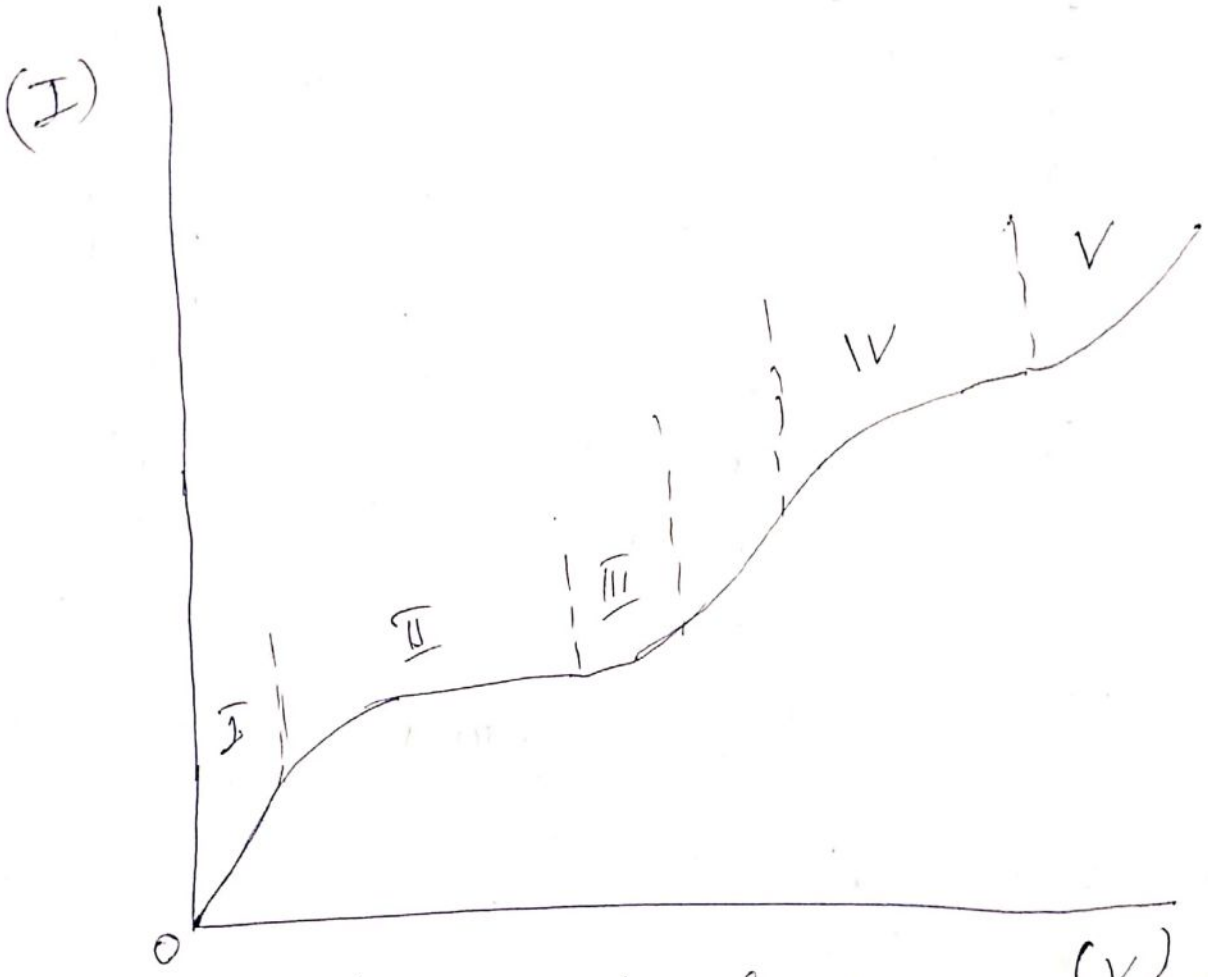

fig 2.2 plot of current as function of (V) applied to the two electrodes A and B of fig 1. Origin of the five region marked I, II, III, IV and V, is explained in the text. Ionization chamber operates in region II, proportional counters

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in III, Geiger-Mueller counters in region IV. The unmarked region is of no practical use.

However under the influence of electric field, which exits b/w the two electrodes, when V is greater than zero, some of the ion pairs reach the electrodes and a transient current is produced in a typical gas filled detector as function of voltage is shown in fig 2.2. There is five distinct regions in this curve.

- In region I, the voltage V is low enough so that some ion pairs produced by radiation are still able to recombine and form neutral atoms or molecules. Here there is an incomplete collection of the ion pairs that are produced by radiation.

- In region II the voltage V is now sufficiently high to attract all the ion pairs produced by the radiation in the sensitive volume of the detector. In this region the amount of current produced by an ionizing radiation does not change appreciably with change in voltage V.

- In region III the voltage is high enough not only to attract all the ion pairs produced by the radiation but also to provide enough energy to some of the primary ion pairs to produce secondary ion pairs by collision with neutral atoms and molecules of the gas. In this region the amount of current vary significantly with change in voltage V.

- In region IV, the voltage is so much higher that the primary ions produced by radiation acquire enough energy to produce a large number of secondary ion pairs and

excitation, which then strike the metallic electrodes and neutral gas molecules to produce more ionization as well as excitation. The de-excitation of the molecules produces ultraviolet (UV) light which travels throughout the total gas volume producing more ionization. The end result of all this is a discharge (a turbulent state of ionization, excitation and UV light) in the total gas volume. In this region the amount of current produced is more or less independent of the voltage V.

- In last region (V), the voltage is so high that the radiation is not necessary to produce discharge. Under the influence of such a high electric field, the electrons are pulled out from the atomic shells, the atoms and molecules become ionized and a discharge may be established even without radiation.

2.3.2 Ionization chambers:

Ionization chambers were one of the earliest types of gas-filled detectors used in radiation measurement. The operating voltage in this detectors lies in region II of fig 2.2, which is important because in this region small changes in voltage do not change current significantly. As a result ionization chambers are highly stable and reliable. Their main disadvantages are their poor sensitivity (intrinsic efficiency) for X or γ-rays and lack of

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energy discrimination.
Their principal use is in measurement of very high fluxes of radiation such as those encountered in diagnostic and therapeutic radiology. They are used in nuclear medecine as dose calibrators to measure the amount of radioactivity in amounts of a few microcuries to curie.

2.3.3 Proportional Counters :

These detectors operate in region III of fig 2.2, where there is a built-in amplification ($\sim 10^6$) of primary ionization through the production of secondary ionization. As a result, a sufficient amount of current is produced by even a single ray. Therefore, these detectors, unlike ionization chambers, can be used to count individual events. Proportional counters require sufficient amount of expertise in their construction as well as their use. Their stability, in reference to time and voltage fluctuations, is not as good as that of ionization chambers. Proportional counters are rarely used in radiation detection.

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2.3.4 Geiger-Mueller (G-M) Counters:

The operating voltage of G-M counter is in the region IV of fig 2.2. The incoming particle in this case causes a discharge in the gas and the amount of current produced is more or less independent of the energy of the radiation as well as the voltage. Once the discharge is established in the gas by a ray, how does one stop the process so that the detector is ready for the next ray? This is accomplished in two ways, either electronically or chemically. Electronically, soon after the initiation of the discharge the voltage V is suddenly reduced to a point at which discharge can no longer be sustained and it is immediately returned to the original value. Chemically, some organic molecules such as alcohols and ethers are introduced in the gas as impurities. The primary function of these organic impurities is known as chemical quenchers, is to absorb the UV light produced during the discharge ~~to stop~~ which then causes the discharge to stop.

- G-M tube counters are the most sensitive gas filled detectors.
- They are stable in reference to temperature

→

and voltage fluctuation.
- They do not have any energy discriminative capabilities
- The principal use of GM counters in nuclear medecine is in radiation protection work for surveying the contamination of surrounding and personnel from X and γ-rays emitting radionuclides.

2.3.5 Cloud chambers:

A cloud chamber is a device used to detect ionizing charged particles. In its most basic form, a cloud chamber is a sealed transparent container holding a super cooled, supersaturated vapor water, alcohol, or aromatic hydrocarbon. Alpha particles or beta particles ionize the saturated vapour as they pass through it. The ionized vapour molecules form nucleation centers for condensation and a visible mist forms along the ionization track. It was invented by charles Wilson in 1911.

2.3.6 Buble chambers:

A bulb chamber is a type of detector closely related to cloud chamber. It is a vessel filled with a super heated transparent liquid used to detect charged particles as they move through the detector. Charged particle deposit sufficient energy in the liquid so that it begins to boil along the ionization track, thereby forming a visible string of bubbles. It was invented by Donald Glaser in 1952.

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2.3.7 Operation of scintillator counter:

(a) The operation of a scintillation counter may be divided into two broad steps.

- Absorption of incident radiation energy by the scintillator and production of photons in the visible part of electromagnetic spectrum
- Amplification of the light by the photo multiplier tube and production of the out put pulse.

(b) Mechanism of scintillation process:-

(i) Ionization radiation passes through the crystal,
(ii) electrons are raised to the conduction band.
(iii) Holes are created in the valence band.
(iv) Excitations are formed
(v) Activation centers are raised to the excited states by absorbing electrons, holes and excitations
(vi) De-excitation is followed by the emission of photon.

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6.3.8. Semiconductor detectors:

(a) Type of semiconductor radiation detectors:

(i) The diffused P-n junction
(ii) The surface barrier detector
(iii) The lithium - drifted detector

(b) lithium - drifted detector

The basic processes that take place in making lithium-drifted detectors are that a p-n junction is formed in piece of p-type material by diffusing lithium (as donor or n impurity) into the surface of the material. Because of its small size and high mobility, lithium rapidly diffuses into the semiconductor lattice. A reverse bias is applied to this junction and the temperature is elevated. The lithium ions move toward the negative potential on the n-type material. This ion drift continues until lithium (donor) concentration exactly balances the acceptor concentration in the p-type material. The result of the drifting process is the creation of an intrinsic region of considerable thickness where the number of donors exactly equals the number of acceptors.

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This intrinsic region acts as the detector depletion region and can be used to detect x-rays and γ-rays. Two types of lithium drifted detectors are used: The lithium-drifted silicon detector [Si(Li) or Silly] used mainly for x-rays and the lithium-drifted germanium [Ge(Li) or Jelly] for γ-rays and x-rays.

(c) Advantage of semiconductor detectors

- linear energy response that is independent of particle type
- extremely good energy resolution.
- small detector size are possible
- Thin windows and are insensitive to magnetic field
- fast charge collection (10^{-8} to 10^{-9} sec)

(d) Disadvantage of semiconductor detectors

- small output signal that requires amplification and shaping
- lower efficiency
- operate at liquid nitrogen temperature (77 K).

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(e) The basic components of ~~detection~~ pulse mode electronic detection system =

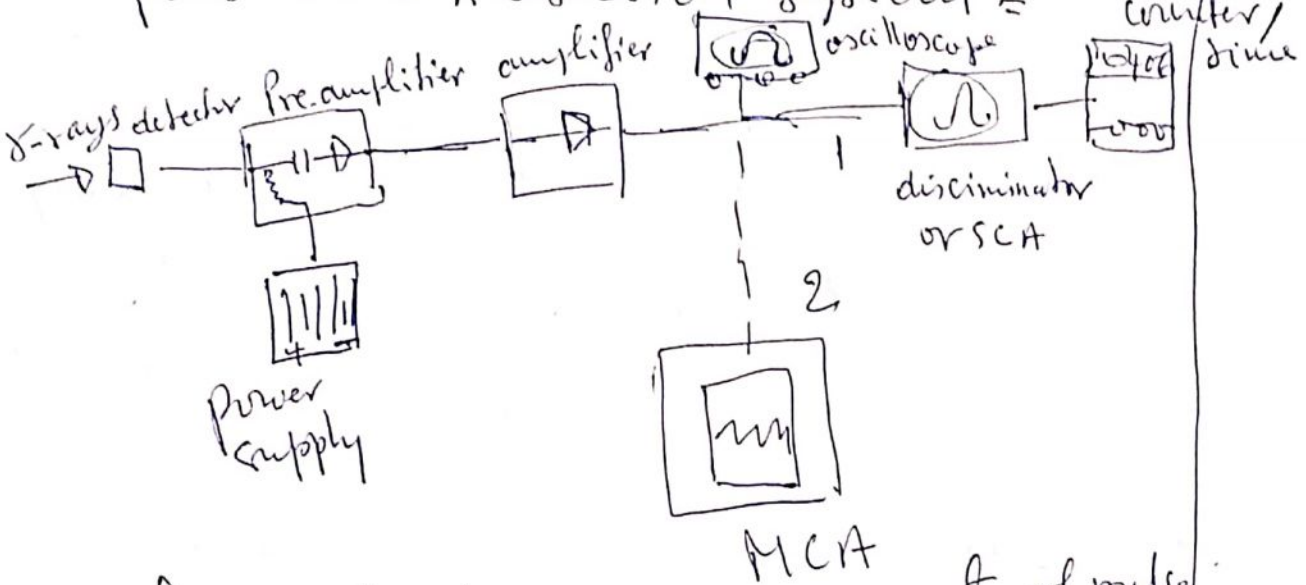

fig The basic components of pulse mode electronic detection system

A detector is powered by a bias supply or power supply, usually through the preamplifier. ~~and amplifier circuits~~ The induced electronic signal from the detector is shaped and amplified through the preamplifier and amplifier circuits. The signal can be observed and monitored with an oscilloscope. When used as a basic counter the shaped signal pulse is routed through a discriminator or single channel analyser (route 1) and then to a counter / timer. When use as a spectrometer the shaped signal pulse is routed to a multichannel analyser (MCA) (route 2) where the pulses are discriminated and categorized according to pulse height.

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Nuclear fission

Definition: The splitting of a heavy nucleus into smaller fragments of approximately equal mass is known as nuclear fission.

There is some mass defect observed during fission, the total mass of the products of fission is less than the total mass of the neutron and the uranium-235 atom. The loss of mass appears in the form of energy according to Einstein's mass energy relation.

$$E = mc^2 \quad \text{——(1)}$$

The nuclear fission of uranium 235 is as

$${}_{92}U^{235} + {}_{0}n^{1} \rightarrow 3\,{}_{0}n^{1} + {}^{92}_{36}Kr + {}^{141}_{56}Ba + \text{Energy}$$

Examples of nuclear fission:

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{140}_{56}Cs + {}^{93}_{37}Rb + 3\,{}^{1}_{0}n + \text{Energy}$$

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{137}_{56}Ba + {}^{97}_{36}Kr + 3\,{}^{1}_{0}n + \text{Energy}$$

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2\,{}^{1}_{0}n + \text{Energy}$$

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Calculation of energy using mass defect concept:

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + \text{Energy}$$

Mass of reactants, $235.044 + 1.0099 = 236.053$ amu

Mass of products, $91.905 + 140.908 + 3.027 = 235.840$ amu

Hence the mass defect $\Delta m = 236.053 - 235.840$

$= 0.231$ amu.

Energy release $= \Delta m c^2 = 0.231 \text{ amu} \times 931.5 \text{ Mev}$

$= 198.41$ Mev

Assignment:

Write down 5 advantages and 5 disadvantage of nuclear fission.

Uses of Nuclear fission:

- Space propulsion applications (rockets)
- radioisotope thermo electric generators for space mission
- Nuclear power plants.
- Drive steam turbine
- Radiation therapy for cancer
- Production of radioisotope used in photographic sources ($Cs-137$)
- Power source for propelling submarines and some type of surface vessels
- Neutrons flux can be used to study structure and properties of materials.

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Nuclear fission :-

S/N	advantage	Disadvantage
1	Produce a large amount of energy	Nuclear power reactor are very compact and capital cost of building is very high,
2	Little amount of fuel required	Reactors require high security
3	less amount of waste product formed	Small leakage from reactor can cause lethal effect
4	No contribution in global warming and pollution	Fuel used in reactors is very expensive and present in trace amount in nature.
5	Maintenance and running costs are relatively low	Possibility of uncontrolled nuclear fission can can cause nuclear fallout
6	Nuclear reactor can ~~deliver for approx. 40 to 60 years.~~	
7.		

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Nuclear fusion:

Nuclides of small mass number combine to form nuclides of higher mass number. In this way the nuclear binding energy will be increased and thus there will be a more stable configuration, such reaction is referred to as fusion reaction. Thus fusion reaction occurs when nuclides of $A \leq 15^-$ combine to form heavier nuclides

In both fusion and fission reactions energy is given off because the nucleons go from a state of lower B.E/nucleon. The energy that is given off is Δ (B.E/nucleon) X N, where Δ(B.E/nucleon) is the change in B.E/nucleon and N is the number of nucleons taking part in the reaction.

- fusion in stars:

$$_1^1H + {}_1^1H \longrightarrow {}_1^2H + \beta^+ + \nu$$

$$_1^1H + {}_1^2H \longrightarrow {}_2^3He + \gamma$$

$$_2^3He + {}_2^3He \longrightarrow {}_2^4He + 2\beta^+ + 2\gamma + 2\nu$$

The resultant reaction of these reactions is

$$4\,{}_1^1H \longrightarrow {}_2^4He + 2\beta^+ + 2\gamma + 2\nu.$$

- other fusion reactions that occurs in stars:

$$_6^{12}C + {}_1^1H \longrightarrow {}_7^{13}N + \gamma$$

$$^{14}_{7}N + {}_1^1H \longrightarrow {}_8^{15}O + \gamma$$

$$_4^7Be + {}_1^1H \longrightarrow {}_5^8B + \gamma$$

$$_2^3He + {}_2^4He \longrightarrow {}_4^7B + \gamma$$

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